RECENT CHALK RIVER EXPERIMENTS ON SUPERALLOWED $0^+ \rightarrow 0^+$ BETA DECAYS

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ABSTRACT

Two experiments, (1) a measurement of the superallowed $0^+ \rightarrow 0^+$ branching ratio in ^{10}C, and (2) a measurement of (or limit on) non-analogue $0^+ \rightarrow 0^+$ branches in ^{38m}K, ^{46}V, ^{50}Mn and ^{54}Co, are described. The implications these experiments have on the test of the conservation of the weak vector current (CVC) and the unitarity of the Cabibbo-Kobayashi-Maskawa matrix are surveyed.

1. Introduction

Superallowed Fermi $0^+ \rightarrow 0^+$ nuclear beta decays[1,2] provide both the best test of the Conserved Vector Current (CVC) hypothesis in weak interactions and, together with the muon lifetime, the most accurate value for the up-down quark-mixing matrix element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, V_{ud}. At present, the deduced value of V_{ud} from nuclear beta decay is such that, with standard values[3] of the other elements of the CKM matrix, the unitarity test from the sum of the squares of the elements in the first row fails to meet unity by more than twice the estimated error.

According to CVC, all Fermi decays should yield a nucleus-independent value of the weak vector coupling constant, $G_{\rm v}$, from their measured ft values provided that small isospin-symmetry-breaking[4,5,6,7] (δ_C) and radiative[8,9] (δ_R) corrections are accounted for. Specifically for an isospin-1 multiplet

$$\mathcal{F}t = ft(1 + \delta_R)(1 - \delta_C) = \frac{K}{2G_{\rm v}'^{\,2}}, \tag{1}$$

where f is the statistical rate function, t the partial half-life for the transition, δ_R is the calculated nucleus-dependent radiative correction, δ_C the calculated isospin-breaking correction, and K is a known[1] constant. The effective coupling constant relates to the primitive one via $G_{\rm v}' = G_{\rm v}(1 + \Delta_{\rm R}^{\rm V})^{1/2}$, where $\Delta_{\rm R}^{\rm V}$ is a calculated nucleus-independent radiative correction. For tests of the CVC hypothesis it is not necessary to consider this correction.

In this report, we highlight two recent experiments[10,11] at Chalk River aimed at shedding light on the two corrections in Eq. (1). By far, the largest contribution to the $\mathcal{F}t$-value uncertainty comes from the calculation of δ_R and δ_C, not from the experimental data. There has been a suggestion that the calculated corrections, to

date, are not complete since the data seem to display a small residual Z-dependence in the $\mathcal{F}t$ values. In this case, the best overall $\mathcal{F}t$ value might be taken from a curve fitted to the individual data and extrapolated[12] to $Z = 0$. In such fits the deduced V_{ud} matrix element is larger and the unitarity test on the CKM matrix satisfied.

In order to establish whether such phenomenological fitting can be justified, two experiments were mounted at Chalk River: (1) to provide a new data point closer to $Z = 0$ by measuring the branching ratio for the lightest superallowed Fermi beta emitter, ^{10}C, and (2) to measure branching ratios to non-analogue 0^+ states in the daughter nucleus, which tests the model predictions for isospin-mixing corrections.

2. The ^{10}C branching-ratio experiment

The decay of ^{10}C takes place mainly through a strong Gamow-Teller transition to an excited 1^+ state at 718 keV in ^{10}B, while only about 1.5% of the decays go to the isobaric analogue 0^+ state at 1740 keV. The superallowed branching ratio is simply given by the ratio of the number of gamma rays at 1022 ($1740 - 718$) keV to that at 718 keV, $i.e.$

$$B(0^+ \rightarrow 0^+) = \frac{R(1022)}{R(718)} = \frac{Y(1022)}{Y(718)} \frac{\epsilon(718)}{\epsilon(1022)}, \tag{2}$$

with R being the emission rate, Y the observed yield, and ϵ the detection efficiency at a given γ-ray energy. Any measurement, however, requires excellent statistics to yield precision of a few parts per thousand on such a weak branch. In addition, since the isobaric analogue state populated by the superallowed branch is deexcited by the emission of a 1022 keV gamma ray, it is necessary to minimize and account for the pileup of 511 keV annihilation radiation that disturbs the measurement.

The experiment was therefore performed on a large gamma-ray array: the 8π spectrometer at Chalk River. Here the total detector efficiency is shared by the N independent detectors, and the pileup-to-signal ratio is decreased by a factor of N. The 8π spectrometer is composed of 20 Compton-suppressed 25% HPGe detectors surrounding a 72-element BGO inner ball. In addition to the twentyfold reduction in the 511 pileup signal obtained because of the geometry of the array itself, a further reduction is obtained via the pileup rejection system on each germanium detector, which has a mean resolving time of roughly 420 ns.

The experiment comprised two interleaved measurements. One, the relative γ-ray yield measurement, was a repeated cycle in which the activity was first produced by a (p, n) reaction on a ^{10}B target mounted in the centre of the 8π spectrometer; then the beam was turned off and the β-delayed gamma rays from the decay of ^{10}C observed in singles mode. The second measurement, that of the relative gamma-ray efficiency, was performed in beam with γ-γ coincidences recorded from the deexcitation of the 2154 keV level in ^{10}B, which was populated by the (p, p') reaction. Further details are given in ref.[10] .

After a number of corrections were applied, the total branch to the isobaric analogue state was determined to be

$$B(0^+ \to 0^+) = [1.4625 \pm 0.0020(\text{stat}) \pm 0.0015(\text{syst})]\%, \tag{3}$$

where the systematic uncertainty is the one attributed to the sum of all experimental corrections; it should be added quadratically to the statistical uncertainty. This result agrees with, but is substantially more precise than, previous measurements: $(1.465 \pm 0.014)\%$, ref.[13] ; $(1.473 \pm 0.007)\%$, ref.[14] ; $(1.465 \pm 0.009)\%$, ref.[15] . When our results are averaged with the previous measurements and combined with $Q_{EC} = 1907.77(9)$ keV[16] and $t_{1/2} = 19.209(12)$ s[17], corrected for electron capture (0.296%), the ft value obtained is

$$ft(^{10}\text{C}) = 3040.1 \pm 5.1s. \tag{4}$$

3. Branching ratios to non-analogue 0^+ states

The charge-dependent correction δ_C, introduced in Eq. (1), reflects differences between the initial- and final-state wavefunctions, and thus is strongly nuclear-structure dependent. The two most complete calculations of this correction by Towner-Hardy-Harvey (THH)[4,5] and Ormand-Brown (OB)[6,7] show qualitative agreement in that the large variations in δ_C from nucleus to nucleus are similar in both models. However, the models differ in their values for the absolute magnitude of the correction.

Both calculations identify two separate contributions to the charge-dependent correction. The larger, radial-overlap part, δ_{RO}, arises from the fact that protons are less bound than neutrons, so the (initial) proton wavefunction imperfectly overlaps the (final) neutron one. The smaller, isospin-mixing part δ_{IM} results from different degrees of configuration mixing in the wavefunctions of members of an isospin multiplet. This latter correction is amenable to experimental test. If we denote the Fermi matrix element for the ground-state transition as $\langle M_0 \rangle$ and that for the non-analogue transition to an excited 0^+ state as $\langle M_1 \rangle$, then, for states with $(J^\pi, T) = (0^+, 1)$,

$$\langle M_0 \rangle^2 = 2(1 - \delta_C) \simeq 2(1 - \delta_{IM})(1 - \delta_{RO}) \tag{5}$$
$$\langle M_1 \rangle^2 = 2\delta_{IM}^1(1 - \delta_{RO}), \tag{6}$$

where δ_{IM}^1 is essentially the admixture of the 0^+ ground state into the first excited 0^+ state. The branching ratio B_1 to the latter is

$$B_1 \approx \frac{t_0}{t_1} = \frac{f_1}{f_0}\frac{f_0 t_0}{f_1 t_1} = \frac{f_1}{f_0}\frac{2\delta_{IM}^1}{2(1 - \delta_{IM})} \approx \frac{f_1}{f_0}\delta_{IM}^1, \tag{7}$$

where subscripts 0 and 1 again indicate the ground state and excited 0^+ state, respectively.

Table 1. Analogue-symmetry-breaking corrections

| | Expt.(%) | Theory(%) | | | |
| | | THH | | OB | |
Nuclide	δ^1_{IM}	δ^1_{IM}	δ_{IM}	δ^1_{IM}	δ_{IM}
^{38m}K	< 0.28	0.096(2)	0.100(2)		
^{46}V	0.053(5)	0.046(5)	0.087(10)	0.054(50)	0.094(50)
^{50}Mn	< 0.016	0.051(23)	0.068(30)	0.015(50)	0.017(50)
^{54}Co	0.035(5)	0.037(8)	0.045(5)	0.003(50)	0.006(50)

Experiments[11] at Chalk River have searched for non-analogue $0^+ \rightarrow 0^+$ transitions in the decays of four superallowed beta emitters, *viz.* : ^{38m}K, ^{46}V, ^{50}Mn and ^{54}Co. Samples of ^{38m}K were produced with (α, n) reactions and of the other three emitters with (p, n) reactions, all on isotopically enriched targets. The experiments were performed at the TASCC facility, with a helium-jet gas-transfer system used to convey activities from the target chamber to a low-background counting location.

A 68% HPGe detector was used to look for the characteristic β-delayed gamma rays from excited 0^+ states in the daughter. Since the non-analogue transitions are very weak (ppm level) strong samples (MBq level) were required. Passive shielding installed in front of the detector crystal prevented direct exposure to the high flux of energetic positrons from the dominant ground-state branch, but the resulting bremsstrahlung radiation was intense enough to obscure any weak gamma-ray branches. To overcome this limitation, two thin plastic scintillators were positioned in front of the HPGe detector and on either side of the collected sample. All recorded gamma rays were tagged with the status of the positron events in the scintillators. With the scintillator information invoked, the level of continuous background in the HPGe spectrum was reduced by a factor of 400 compared to the singles result. This permitted the observation of β-delayed gamma-ray branches down to the 10 ppm level.

The results obtained on the four superallowed β emitters are given in Table 1, together with theoretical values computed by THH[5] and updated in[11] , and by OB[7] . The THH calculations are in good agreement with experiment for ^{46}V and ^{54}Co but overestimate slightly for ^{50}Mn. OB were able to reproduce the ^{46}V result and the ^{50}Mn limit, but these authors had difficulty with their shell-model calculations for ^{54}Co, which they discuss in their manuscript[7] . The authors assigned a large error estimate to all their δ_{IM} computations. On balance, the calculations are in reasonable agreement with experiment showing that this part of the isospin-symmetry-breaking correction is under control.
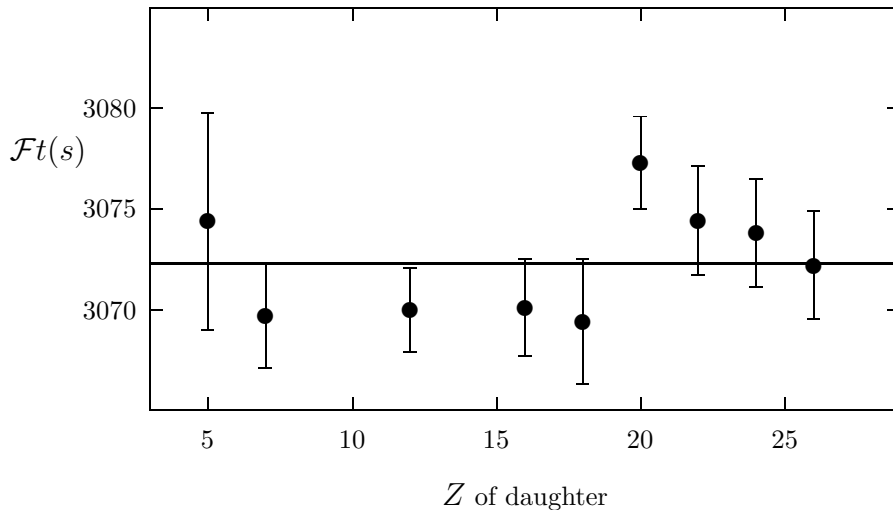
Fig. 1. $\mathcal{F}t$ values for the nine precision data and the best least-squares one-parameter fit

4. Current status

World data on Q-values, lifetimes and branching ratios were thoroughly surveyed[1] in 1989 and updated again[2] this year. The ft-values and δ_R correction are taken from this latter reference. Ormand and Brown[7] have just released a revised calculation of δ_C but, as with their earlier calculation[6] , there is a systematic difference from that of THH[4] ; however the magnitude of this difference is reduced by about a factor of two. This difference represents a 'systematic' uncertainty of $\pm 0.04\%$ that is put to one side for the test of CVC, but must be applied at a later stage to the average $\mathcal{F}t$ value. We adopt for δ_C the unweighted average of the THH and OB values.

The results for the nine $\mathcal{F}t$ values are displayed in Fig. 1. The uncertainties shown reflect the experimental uncertainties and an estimate of the *relative* uncertainties in δ_C. There is no statistically significant evidence of inconsistencies in the data ($\chi^2/\nu = 1.2$), thus verifying the expectation of CVC at the level of 4×10^{-4}, the fractional uncertainty quoted on the average $\mathcal{F}t$ value (3072.3 ± 1.0 s). In using the average $\mathcal{F}t$ value to determine V_{ud} and test CKM unitarity it is important to incorporate the 'systematic' uncertainty in δ_C just referred to. The result is

$$\mathcal{F}t = 3072.3 \pm 2.0 \text{ s}. \tag{8}$$

With this value, an estimate[18] of the nucleus-independent radiative correction of $\Delta_R^V = (2.40 \pm 0.08)\%$, and the weak vector coupling constant[3] derived from muon decay, we obtain

$$V_{ud} = 0.9740 \pm 0.0005. \qquad (9)$$

The quoted uncertainty is dominated by uncertainties in the theoretical corrections, $\Delta_{\mathrm{R}}^{\mathrm{V}}$ and δ_C. On adopting the values[3] of V_{us} and V_{ub} from the Particle Data Group, the sum of squares of the elements in the first row of the CKM matrix,

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9972 \pm 0.0013, \qquad (10)$$

differs from unity at the 98% confidence level.

The significance of this apparent non-unitarity is not yet settled. It may, of course, indicate the need for some extension to the three-generation Standard Model – perhaps in the form of right-hand currents or additional gauge bosons. However, it may also reflect some undiagnosed inadequacy in the evaluation of V_{us} (as already suggested for other reasons in ref.[19]) or possibly in the δ_C corrections used to determine V_{ud}. There is little scope left by the data in Fig.1 for introducing significant additional Z-dependence in δ_C, as has been suggested recently[12].

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